



# **Physics Based Analysis of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) for Radio Frequency (RF) Power and Gain Optimization**

**by Pankaj B. Shah and Joe X. Qiu**

**ARL-TN-0465**

**December 2011**

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) December 2011		2. REPORT TYPE		3. DATES COVERED (From - To)
4. TITLE AND SUBTITLE Physics Based Analysis of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) for Radio Frequency (RF) Power and Gain Optimization		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Pankaj B. Shah and Joe X. Qiu		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-SER-E 2800 Powder Mill Road Adelphi, MD 20783-1197		8. PERFORMING ORGANIZATION REPORT NUMBER  ARL-TN-0465		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT <p>The power and gain characteristics of a power radio-frequency (RF) gallium nitride (GaN) high electron mobility transistor (HEMT) were investigated by using drift-diffusion model simulations that were self consistently solved with the current-voltage (I-V) characteristics of the external circuit elements. The results showed the expected drop in gain with frequency, as the corresponding output power increases, can be modeled with device physics considerations. This technique can be used to optimize device performance by determining which part of the device to modify for greatest impact.</p>				
15. SUBJECT TERMS Power amplifier, distortion				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES  14
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		
				19b. TELEPHONE NUMBER (Include area code) (301) 394-2809

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## 1. Introduction

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Gallium nitride (GaN) radio frequency (RF) devices have recently exhibited advances such as good reliability at low power and performance that allows them to enter the commercial market and compete with other devices as evidenced by the RF products available on such Web sites as Cree Inc., Triquint Semiconductor, and RFMD. Having reached this point in their development, researchers can now investigate more complex circuits and operational modes. To optimize the devices and push material and device designs to their limits, simulations are necessary. Embedding the device in a circuit for these simulations helps optimize the device performance for real applications.

Important issues for GaN high electron mobility transistors (HEMTs) in RF applications are power and linearity performance. The linearity of a GaN HEMT is tied to the internal gate-source capacitance ( $C_{gs}$ ), gate-drain capacitance ( $C_{gd}$ ), transconductance ( $G_m$ ), and drain conductance ( $G_d$ ). All of these are determined by the charge carrier flow and energy barriers they encounter; depletion regions; and internal electrostatic potential distributions in a semiconductor device. Power output is also tied to carrier transport behavior, device current, power gain, electric field distributions, etc. Understanding the relationship between these physical characteristics and RF performance will greatly speed the application of GaN devices in advanced RF systems. Towards this end, we have performed drift-diffusion-based simulations of a GaN HEMT operating as a class A amplifier.

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## 2. Procedure

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Simulations were performed using the drift-diffusion simulations software Atlas/Blaze provided by Silvaco Inc. to solve Poisson's equation and the charge carrier continuity equations over a two dimensional cross section of the device. Mixed-mode simulations were also performed wherein external circuit elements are included along with the device and additionally the currents and voltages of the external elements are self consistently solved for and included in the solution process. The GaN HEMT structure is shown in figure 1.

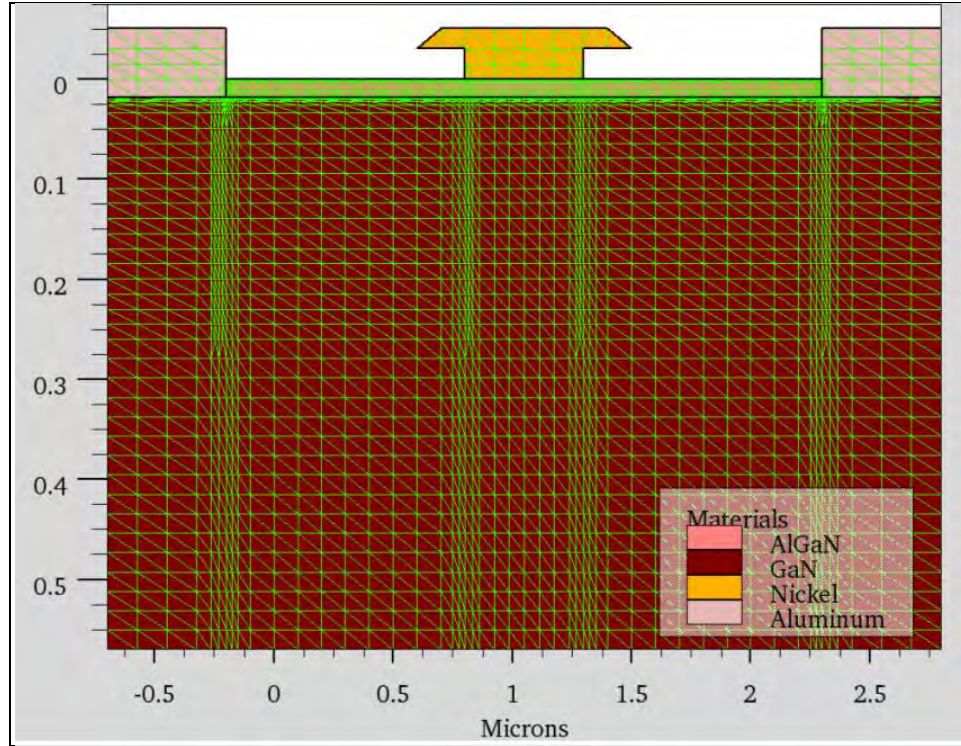


Figure 1. Simulated GaN HEMT.

The device consisted of a 19-nm aluminum gallium nitride (AlGaN) barrier layer containing 28% aluminum (Al) above a GaN layer. The HEMT gate length was 0.5  $\mu\text{m}$ . GaN and AlGaN models used in the simulations included Shockley-Read-Hall recombination; concentration and field dependent mobility<sup>1</sup>; and polarization charges at the interface. Also, a 1-eV Schottky barrier height was considered.

Mixed-mode simulations were performed in Atlas/Blaze, embedding the device in the circuit, as depicted in figure 2. The inductor L blocks the RF signal to the DC power supply and the capacitor C blocks the DC bias from the load resistor  $R_L$ .  $R_d$  and  $R_s$  are the contact resistances of the HEMT. The contact resistances were set to 1.5  $\Omega\text{-mm}$ .

<sup>1</sup>Farahmand, M et al. *IEEE Trans. Elect. Dev.* **2001**, 48, 534.



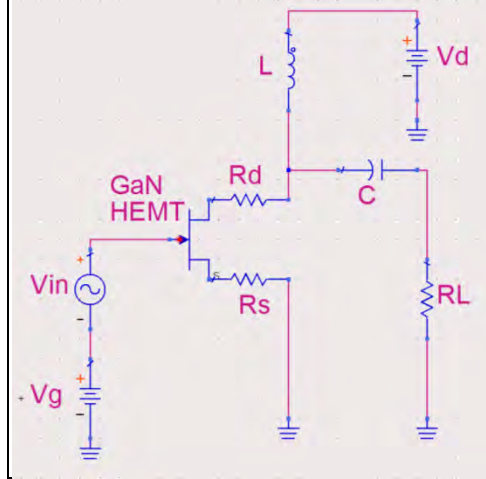


Figure 2. Circuit simulated in Atlas mixed mode.

Following the mixed mode simulations, the RF output waveform was read into Mathcad, where it was first interpolated to uniformly space the discrete points of the output waveform. Then, a Fourier transform was taken followed by calculating the average RF power entering the HEMT and total power in the first harmonic at the output of the HEMT. This output power out is calculated from the product of the fundamental frequency component of the load current and load voltage.

### 3. Results

The current-voltage (I-V) characteristics obtained from a non-mixed-mode, drift-diffusion simulation of the device are plotted in figure 3. These I-V characteristics match typically fabricated GaN devices. A slight soft pinchoff is exhibited for the  $V_g = -6$  V curve.

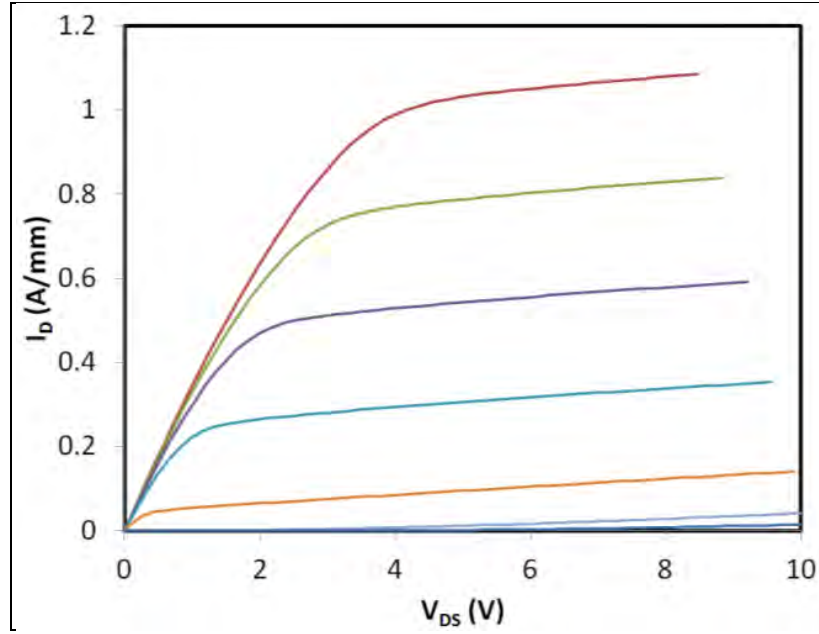


Figure 3. I-V characteristics of the GaN HEMT. The curves from top to bottom are for  $V_g = 0, -1, -2, -3, -4, -5$ , and  $-6$  V.

For the RF simulations  $V_d$  was set to 20 V and  $V_g$  was set to  $-3$  V. The current in the load obtained for an input source at 100 MHz is shown in figure 4. There we see the waveform is compressed at negative values due to the current in the transistor reaching the knee of the I-V curves.

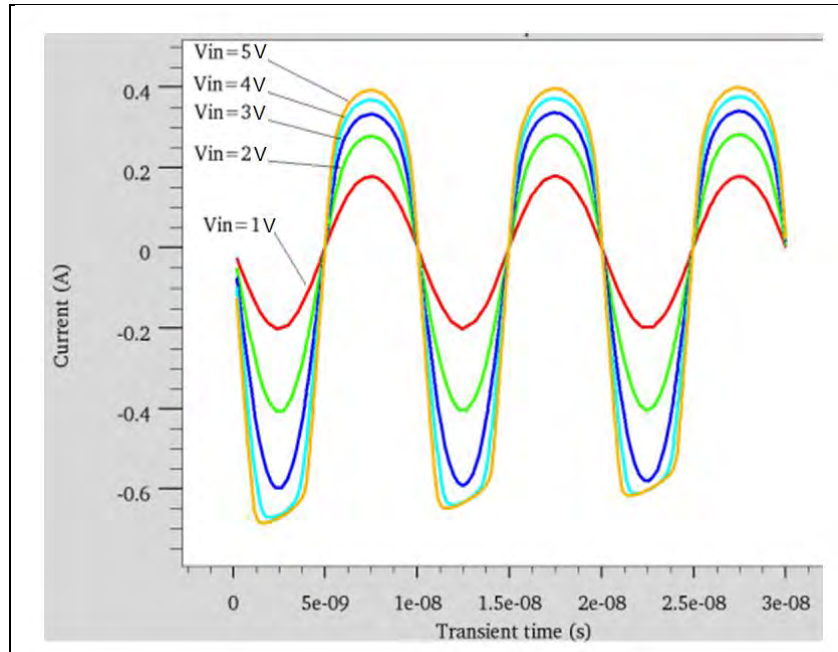


Figure 4. Load current waveforms for input sinusoidal voltage ( $V_{in}$ ) amplitudes of 1, 2, 3, 4, and 5 V. The input frequency is 100 MHz.

The power output vs. power input is shown in figure 5 for a 100-MHz input RF source, and in figure 6, for a 10-GHz input RF source.

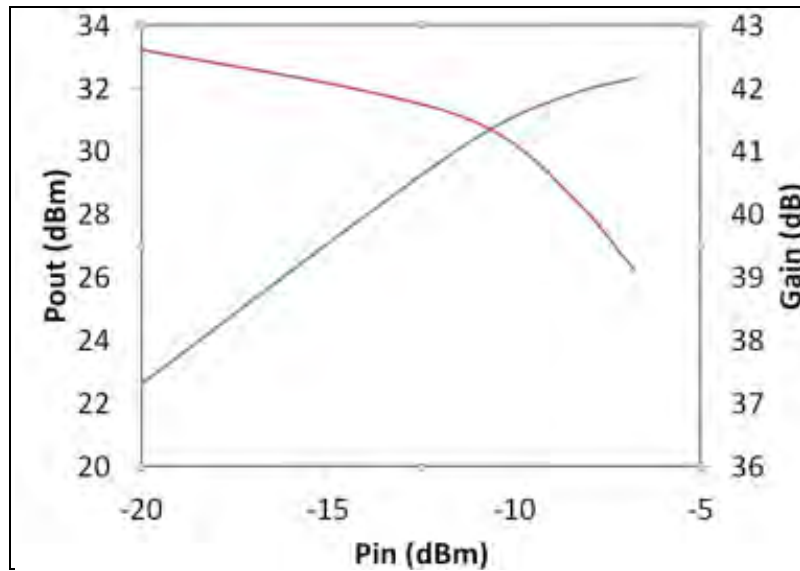


Figure 5. Calculated power output and gain at 100 MHz. Blue curve is the power, red curve is the gain.

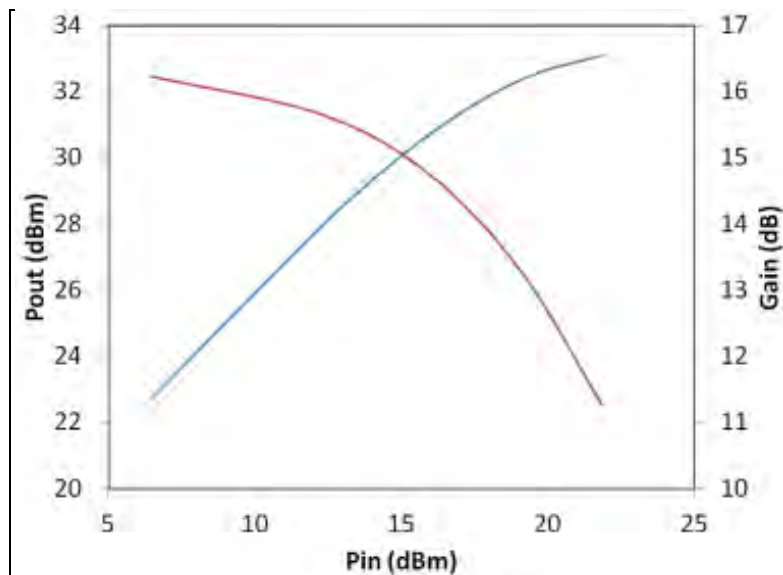


Figure 6. Calculated power output and gain at 10 GHz. Blue curve is the power, red curve is the gain.

The results exhibit the expected lower gain at higher frequencies due to internal impedances of depletion regions, and charge carrier velocity limitations. Also, we observe the output power compression occurring as gain begins to drop rapidly.

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## 4. Conclusions

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The power and gain characteristics of a GaN HEMT were investigated by using drift-diffusion model simulations that were self consistently solved with the I-V characteristics of the external elements. The results showed the expected drop in gain with frequency, as the corresponding output power increases, can be modeled considering device physics. This technique can be used to optimize device performance by determining which part of the device to modify for greatest impact. This technique could also be expanded by using additional RF sources to analyze intermodulation distortion.

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